Lidar Profiling of Sound Speed & Temperature in the Ocean Upper Mixed Layer

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LONG-TERM GOALS

My long-term goals are the exploitation of physics for the solution of significant problems in oceanography. My interests generally lie in the direction of optics and laser interactions/applications in the ocean.

OBJECTIVES

An important Navy and oceanographic requirement is the rapid and accurate determination of sound speed (and hence temperature) profiles in the ocean. Our objective is development and implementation of the first successful approach to the remote sensing acquisition of upper-ocean vertical sound speed profiles. To this end we are developing an innovative Brillouin LIDAR concept that will provide measurements of temperature and sound speed to an accuracy of 0.1°C and 0.2 m/s, respectively over a range of ≈100 m with a range resolution of ≈1 m. Our latest results clearly demonstrate the feasibility of this exciting new approach.

APPROACH

When a narrow linewidth laser beam propagates through water, it undergoes Brillouin scattering which consists of two frequency shifted Lorentzian lines centered symmetrically with respect to the frequency of the transmitted laser line. In pure water, the scattering spectrum consists of essentially only this doublet. However, in the presence of suspended particulate matter (hydrosols), an elastically scattered central line (also called the unshifted line, or improperly, the Rayleigh line) appears. The so-called Brillouin shift, that is to say the frequency shift between the central line (the laser frequency) and each of the Brillouin lines, is typically 7 to 8 GHz for water. The shift is proportional to the refractive index and the sound speed in the water; hence, it also has dependence on the salinity and temperature.

Figure 1 illustrates our detection apparatus to measure sound speed (temperature) based on the Brillouin shift in a LIDAR return. First, the LIDAR return is collimated to an approximately 1.0 cm diameter beam and is then passed through an absorption cell containing $^{127}I_2$. The laser frequency is tuned so that its second harmonic at 532 nm lies on a strong absorption line of $^{127}I_2$; consequently, this first absorption cell absorbs all of the elastically scattered light. The transmitted light is divided by a 50-50 beamsplitter into two equal parts, one of which is detected and provides the normalization signal S_1. The second half passes through an absorption cell containing $^{129}I_2$ and is detected to give the signal S_2. The edges of molecular absorption lines of $^{129}I_2$ provide the high spectral resolution that is needed for an accurate determination of the Brillouin frequency shifts. Specifically, as the Brillouin shift increases (decreases) the transmission of the $^{129}I_2$ cell decreases (increases). Simple normalization provides a signal S that depends only on the Brillouin shift and is independent of variations in the amplitude of the LIDAR return; for example, the Brillouin shift is proportional to either $S_2/(S_1 - S_2)$ or S_2/S_1. Determination of the proportionality constant is straightforward via measurements of a water sample with known temperature. The concept is extraordinarily simple and robust.
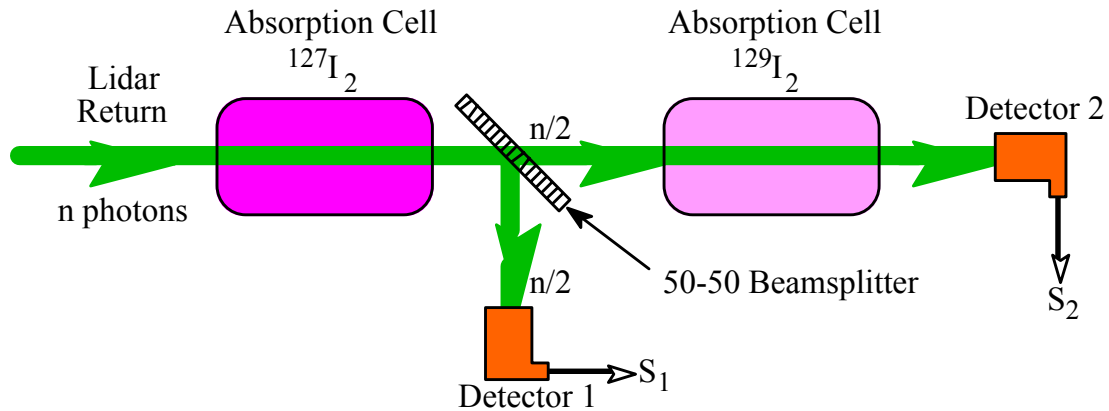
Figure 1. The lidar return first passes through a $^{127}I_2$ cell that absorbs elastically scattered light. The transmitted light consists of the two Brillouin shifted lines; half is detected to give signal S_1. The other half passes through the $^{129}I_2$ cell (edge filter); the transmitted part gives signal S_2. The ratio $S= S_2/S_1$ uniquely determines the Brillouin shift.

Key individuals in addition to the PI that are participating in the work are (1) Dr. Gangyao Xiao: He received his Ph.D. from the Institute of Optics and Fine Mechanics in Shanghai, China. Prior to joining our group in August of 1998, he was an Associate Professor at the National Laboratory on High Power Lasers & Physics in China. (2) Mr. Jeffrey Katz: He is a graduate student working full time on the project; this work is the basis of his Ph.D. dissertation. (3) Mr. Remus Nicolaescu: He is a graduate student working part time on the project; he has been a major contributor to the laser development required in the early stages of the project.

WORK COMPLETED

(1) We have successfully modified the Continuum laser so as to operate at 1064.77 nm, which is a wavelength for which $^{127}I_2$ will absorb elastically scattered light and $^{129}I_2$ will provide an edge filter for the Brillouin shifted lines. Operation at this wavelength required an increase in the operating temperature of the laser rod and involved separating the cooling systems for the laser rod and flashlamps. We then used a constant temperature bath at 95°C to circulate hot water over the laser rod and appropriately adjusted the cavity optics.

(2) As part of the effort required for adjustment of the operating wavelength of the laser, we replaced the single frequency, monolithic, diode pumped seed laser that is supplied with the Continuum laser with a distributed feedback (α-DFB) laser diode. The latter provided the wide tuning range essential to obtaining seed laser operation at 1064.77 nm. Since the stability of its frequency is critical, we also built a simple (relatively crude) feedback system to lock the frequency of the laser diode so that its second harmonic corresponded to the frequency of the required $^{127}I_2$ absorption line.

(3) We also completed implementation on our Continuum laser of the Ramp and Fire technique [1, 2] that we had previously developed for injection seeding pulsed lasers. Our commercial laser, purchased from Continuum, is delivered with an injection seeding system based on a technique known as the Pulse Build-Up Time; it requires approximately 1/2 hour to warm up before operating reliably, and it is very sensitive to environmental disturbances (noise and vibrations). Our Ramp and Fire technique is significantly more robust [2]; in fact, the laser now operates in a single longitudinal mode on every shot

from the very first shot without any warm-up and even when the covers have been removed so that the laser head is open to air currents.

(4) Finally, we have completed the assembly of the entire system described in Figure 1 and have used it to obtain our first measurements of the ratio S= S_2/S_1. This is the most important work that we have completed since it provides solid verification of the entire conceptual approach.

RESULTS

The results of our modifications to the commercial Continuum laser have been successful as outlined in the first three items of "WORK COMPLETED" listed above. Specifically, we have: (a) changed the operating wavelength of the laser to 1064.77 nm; (b) implemented the robust Ramp and Fire seeding technique; (c) replaced the seed laser with an α-DFB diode laser; and (d) locked the second harmonic frequency of the α-DFB diode laser to the $^{127}I_2$ absorption line.
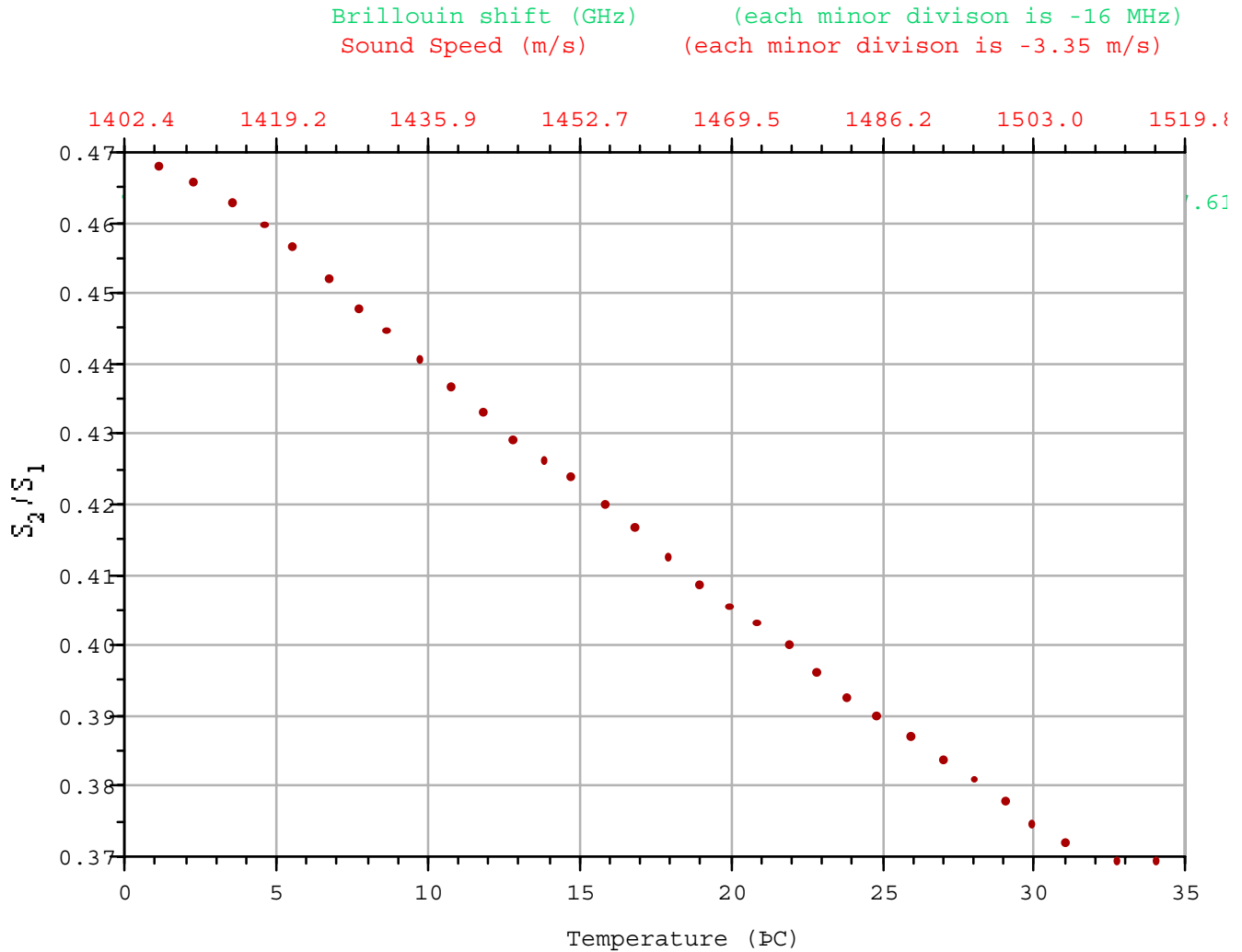
Figure 2. Observed signal as a function of temperature for pure water. The auxiliary axis at the top shows the corresponding Brillouin shift and sound speed.

In Fig. 2 we show the first data from tests implementing the concept shown schematically in Fig. 1 for the Brillouin shift frequency discrimination. For this data we used a sample of pure water (0 ‰ salinity) that was ≈50 cm deep; so there was no depth discrimination, we just looked at the frequency shift of the total back-scattered signal. Specifically, we measured the signal $S= S_2/ S_1$ as a function of the temperature of the water sample. Since temperature, sound speed and Brillouin shift are uniquely related in pure water [3], the plot in Fig. 2 shows the signal S as a function of the measured temperature of the water with an additional axis at the top showing the corresponding Brillouin shift and derived sound speed. The data point at each temperature (sound speed) corresponds to a single laser shot.

The errors at each point are such that the sound speed is determined to an accuracy of better than 75 cm/s; and, this high accuracy is obtained with a <u>single</u> laser shot! Furthermore, these are our first results and improvements are forthcoming; in addition, averaging over several shots can provide further significant improvements. There are two other important factors limiting the accuracy in the above data. First, our temperature measurements had an accuracy of ±0.2 ˚C; a new Platinum RTD thermometer (accuracy ±0.02 ˚C) will be obtained for future work. Second, a problem inherent to any detection system using normalization based on two different photomultiplier tubes is the slight variations in their relative gains due to aging differences and environmental factors. This problem is being solved by implementing a two shot scenario in which the photomultiplier tubes for detecting S_2 and S_1 are effectively interchanged between laser shots.

The results shown in Fig. 2 provide a major milestone. They clearly show that the concept proposed for extracting Brillouin shifts works extremely well!

IMPACT/APPLICATIONS

The technology we are developing to remotely sense profiles of temperature and sound velocity in the ocean will provide the capability of rapidly monitoring the upper-ocean vertical structure for much of the world's oceans and for most seasons. Such profiles will provide new perspectives on upper-ocean mixing and the oceanic internal wave field. Because of the high heat capacity and circulation in the oceans, temperature profiles are of critical importance to weather forecasting and to the understanding of ocean/atmosphere coupling and global change. Finally, sound velocity profiles are of direct strategic importance to the military mission since they provide support for both active and passive sonar functions; they would also provide an extensive new subsurface data source for operational nowcast/forecast systems.

TRANSITIONS

No transitions to the commercial arena have yet occurred.

However, the efforts have attracted considerable interest elsewhere. In particular, <u>Dr. Dahe Liu,</u> who is a professor from Beijing University and who was a visiting scholar in my laboratory in 1997 and 1998, is attempting a similar development in China. He is the one that helped us acquire the iodine isotope ^{129}I from China; it is required for the frequency analysis of the LIDAR return. (As a consequence of government regulations, no U.S. company was willing to process the small amount of ^{129}I we needed; even though, as a fission reactor by-product, there is a plentiful supply in the U.S. I recently visited his laboratory (August 1999). Another researcher in China, Dr. Zhishen Liu, is at the Ocean University of Qingdao. He has been closely following this work in the literature and has visited our laboratory; I visited him in Qingdao last summer. He would like to send a student and/or post-doc to work with us.

RELATED PROJECTS

1 - This project was co-funded with a grant from the Texas Advanced Technology Program entitled "Brillouin LIDAR for Ocean Temperature/Sound Velocity Profiling, Mine Detection, and Bathymetry

2 - In a direct spin-off from this project, we have developed a new concept for detection of submerged objects. It is a particularly significant advance in that even if an object is near or at the surface, it can still be detected with nearly 100% visibility; there are no problems with water surface reflections or bright daylight conditions.

REFERENCES

1. S. W. Henderson, E. H. Yuen and E. S. Fry. 1986: "A Fast Resonance Detection Technique for Single Frequency Operation of Injection Seeded Nd:YAG Lasers," Opt. Lett. <u>11</u>, 715-717.

2. Edward S. Fry, Qiquan Hu, and Xingfu Li. 1991: "Single-Frequency Operation of an Injection Seeded Nd:YAG Laser in High Noise and Vibration Environments", Appl. Opt. <u>30</u>, 1015-1017.

3. V.A. Del Grosso. 1974: "New Equation for the Speed of Sound in Natural Waters (with Comparisons to Other Equations)", J. Acoust. Soc. Am. **56,** 1084-1091.

PUBLICATIONS

1. Yves Emery, Anett Fleischhauer, Thomas Walther, and Edward S. Fry. 1999: "Angle Tuned Type II External-Cavity Frequency Doubling Without Temperature Stabilization", Appl. Opt. 38, 972-975.

2. Remus Nicolaescu, Thomas Walther, Martin Muendel, and Edward S. Fry. 1999:"Ultra-Narrow Linewidth, Efficient Amplification of Low Power Seed Sources by a Fiber Amplifier", Appl. Opt. 38, 972-975.

3. Robin M. Pope, Alan D. Weidemann, and Edward S. Fry. 1999: "Integrating Cavity Absorption Meter Measurements of Dissolved Substances and Suspended Particles in Ocean Water", Dynamics of Atmospheres and Oceans 586, in press.

4. Edward S. Fry. 1999: "Visible and Near-Ultraviolet Absorption Spectrum of Liquid Water (Comment)", accepted by Applied Optics, August 1999.

PATENTS

"Apparatus and Method for Detecting Underwater Objects", U. S. Provisional Patent Application Serial No. 60/117,484.